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Multimode interference waveguide switch of electro-optic polymer with tapered access waveguides

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Abstract

High speed optical switch is a key device for optical communications system. Many kinds of multimode interference (MMI) waveguide switch have been reported by using thermo-optical polymer whose response time is limited in milisencond orders. In order to obtain a high speed and low energy consumption properties, electro-optic (EO) polymer have been studied for a long time. However, it is difficult to use EO polymer in MMI because the change of refractive index of EO polymer is small. In this work, we propose an EO polymer MMI waveguide switch with tapered access waveguides. The device consists of the tapered waveguides and multimode waveguide, where the interference condition and the light propagation are controlled by the change of the refractive index of EO polymer. Results of the beam propagation calculation show that the large effect of switching can be achieved by EO polymer having electro-optic coefficient (r_{33}) of 100 pm/V. The cross talk in the device researches at 30 dB for both TE and TM polarizations. The figure-of-merit given by the products of half-voltage (V) and the active length (L) of the electrode was estimated to be $VL=0.5\text{Vcm}$.

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Keywords: multimode interference, EO polymer, optical switch, tapered structure, self-imaging spot

Introduction

Optical switching devices have drawn a lot of interests in the past decades owing to increasing number of channels required for the information and communications technology. The most widely investigated devices are fabricated based on the optical waveguide structures including interference switches, digital-optical switches, and directional couplers. Particularly, Mach-Zender interference (MZI) and multimode interference (MMI) waveguide devices have been widely used in commercial appalcitins. Compared with MZI waveguides, MMI waveguides have the advantages in compactness, easy fabrication, loose fabrication tolerance, and polarization insensitivity[1,2,3,4]. Chuang and Liao demonstrated thermo-optic polymer MMI waveguide switch by changing the refractive index to shift the phase of the propagating light in the multimode section [6]. In such devices, change of the refractive index is induced thermally by the electric heater, which limits the speed of switching time in milliseconds and requires a relatively high electric power for the switching operation.

Instead of thermo-optical polymer, electro-optic (EO) materials have been studied for high-speed and low electric power photonic devices. Compare to thermo-optic polymers, EO polymers have gained considerable momentum due to the realization of nonlinear optical chromophores capable of providing large EO coefficients at wavelengths of 1.3 μm and 1.55 μm . Recently development of EO polymers with the electro-optic coefficients (r_{33}) larger than 100 pm/v accelates the optical device application for ultra-fast MZI waveguide modulators. Although these r_{33} values are much larger than that for the inorganic crystals, the refractive index change (Δn) of EO polymer is still small for the aplicaiton of MMI waveguide switches. Generally, MMI waveguide switch requires Δn in the order of 1×10^{-3} , while the EO polymer shows Δn of about $2\text{--}6 \times 10^{-4}$. Therefore, the design of MMI structure for the use of EO polymer becomes an important issue to achieve the high-speed optical swiching application. In this work, we introduced tapered access waveguides to the MMI structure, where the self-imaging spot can be effectively modified by the materials though they have rather small refractive index change.

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2. MMI Principle and Design

2.1 MMI Principle

MMI waveguide switch consists of two parts: multimode waveguide and access single mode waveguides. The multimode waveguide supports a large number of modes, where the multimode interference occurs. Figure 1 shows the 1×2 MMI structure studied in this work. The input single mode waveguide is bounded to the center of the multimode waveguide. Two output single mode waveguides are placed at the symmetrical positions. In this structure, input field is launched from the input waveguide, and then guided modes are excited and interfered in the multimode waveguide to produce self-imaging spots of an input field. Due to the modes coupling at different phase, light in the multimode waveguide exhibits various distributions as it propagates in the different lengths determined by the beat length (L_π) of the first two modes. L_π is expressed as,

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_c w_g^2}{3\lambda_0} \quad (1)$$

where β_0 and β_1 are the propagation constants of the first two guided modes, n_c is the refractive index of the core layer, and w_g is the effective width of the MMI part, respectively.

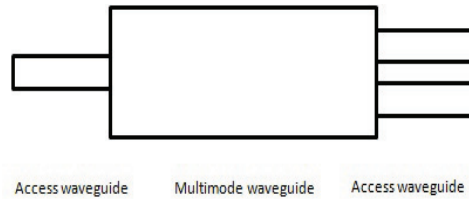


Figure 1. Schematic picture of 1×2 MMI structure.

Switching the light in the device is carried out by the change of the refractive index around the most crucial self-imaging spots appeared in the MMI part. For EO polymer, electrodes should be placed on these spots to induce the change of the refractive index by applying AC or DC electric fields.

2.2 Design of MMI Waveguide

2.2.1 Cross-sectional Design

In order to design the planar configuration of the EO polymer waveguides, we first selected the materials for the fabrication of clad and core layers. Figure 2 shows the cross-section of an invert rib structure designed for the single mode waveguide application. The clad and core materials are selected so that the refractive index of the core layer is larger than that of the clad layer in order to achieve optical confinement in the vertical direction. The rib structure provides a single mode light confinement in the lateral direction. For device fabrication, we designed geometric parameters, such as inner rib width and height and the outer rib height by using FD-BPM calculation. In this calculation, refractive indices of 1.62 and 1.51 at the wavelength of 1.55 μm are used for core and clad layers, respectively.

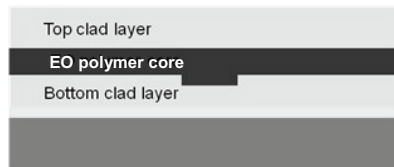


Figure 2. Cross-section of the rib waveguide on silicon substrate.

2.2.2 Tapered Access Waveguide Design

It is difficult for the fabrication of the MMI waveguide switch by using EO polymers because of the drawback of the fact that the refractive index change of EO polymer is smaller than the value required for the switching device. In order to fabricate the EO polymer MMI waveguide switch, we used the tapered structures in the input and output waveguides as shown in Figure 3.

There are two ways to increase the size of the self-imaging spots [5], thereby EO polymer can be used for the application of MMI optical devices. One way is increasing the width of the multimode waveguide. The other way is increasing the width of the access waveguides. However, both of these ways have shortages: the first way leads to large L_π according to the equation 1; the second way is limited by the single mode condition. In this work, we proposed tapered access waveguides to increase the area of self-imaging spots. Therefore, the device consists of MMI waveguide with $W_m=40\text{ }\mu\text{m}$ and $L_m=4355\text{ }\mu\text{m}$ and tapered waveguides with $W_1=4\text{ }\mu\text{m}$, $W_2=16\text{ }\mu\text{m}$, and $L_0=1000\text{ }\mu\text{m}$.

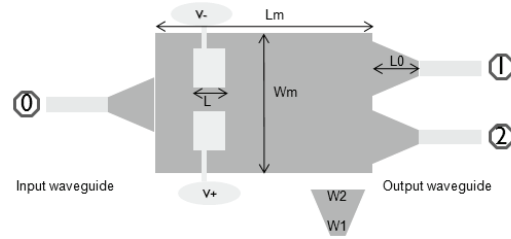


Figure 3. Schematic image of the MMI optical switch with tapered access waveguides.

3. Results and Discussion

Operation of the MMI waveguide switch is as follows: in the absence of an applied electric field between electrodes, light propagates to the output waveguides with a splitting ratio of 1:1 as shown in Figure 4a; when electric field is applied to the EO polymer which causes π phase shift at the electrode area, light will be imaged onto one of the output waveguide (Figure 4b and Figure 4c). In our design, the maximum refractive index change required for the phase shift is estimated to be $\Delta n = 5 \times 10^{-4}$. This level of refractive index change can be achieved by EO polymers.

Design of tapered waveguides and electrodes is the crucial topic for obtaining high performance MMI waveguide switch. The cross talk of the output light from two waveguides is defined as,

$$\text{Cross Talk} = \text{Abs} [\text{Log} (I_1 / I_2)] \quad (2)$$

where I_1 and I_2 are the light intensities emitted from output waveguides 1 and 2, respectively. The sizes of electrodes are limited by the size of the imaging spots which is depended on the size of the access waveguides.

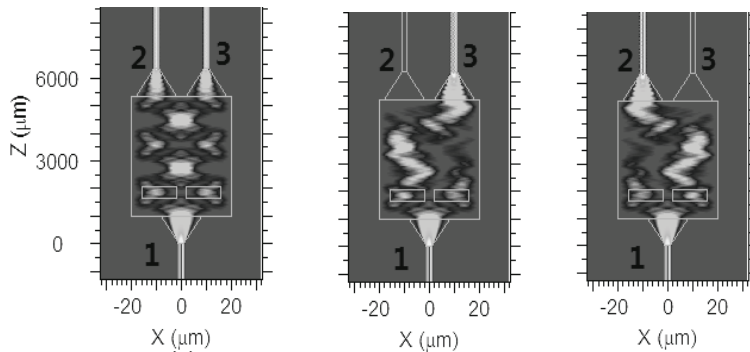


Figure 4. Beam propagation characteristics of three states of the MMI waveguide switch.

Tapered structures have been widely used to increase the coupling efficiency of waveguide devices [9]. In our design, tapered waveguide is also used to modified the distribution of the light field. This modification results in the large self-imaging spots in the MMI waveguide. In order to determine the area of self-imaging spots, W_2 of the tapered waveguide was varied between 4 μm and 16 μm , while keeping $W_1=4 \mu\text{m}$ and the $W_m=40 \mu\text{m}$. Results are summarized in Table 1, showing the change of area of self-imaging spot at different W_2 . The size of self-imaging spot increased as the W_2 increases. For $W_2=4 \mu\text{m}$ with no tapered structure, area of the spot is 145 $\mu\text{m} \times 3.1 \mu\text{m}$. Spot area increased up to 378 $\mu\text{m} \times 12.4 \mu\text{m}$ for $W_2=16 \mu\text{m}$. Compared with the access waveguide with $W_2=4 \mu\text{m}$, tapered structure increased the area of the self-imaging spot in both length and width. This increment brings a possibility to use EO polymer for MMI waveguide switch application.

Table1. The area of self-imaging spots using tapered access waveguide with various lengths of W_2 .

W_2 (μm)	4	6	8	10	12	14	16
Area (μm^2)	145×3.1	181×5.1	197×6.0	250×8.3	274×9.4	343×10.6	378×12.4

With tapered access waveguides, the optimum size of electrodes can be estimated to obtain the largest cross talk for both TE and TM polarizations at the wavelength of $1.55\ \mu\text{m}$. The optimum size of the MMI waveguide was defined as $L_e=448\ \mu\text{m}$ and $W_e=14\ \mu\text{m}$. To demonstrate light switching property in designed MMI waveguide, electric field was applied to the electrodes between $-1\ \text{V}$ and $1\ \text{V}$. Here, we supposed that the maximum refractive index change of 5×10^{-4} was induced at such electric fields. Figure 5 shows the change of output light intensities from the waveguides 1 and 2 plotted as a function of the applied electric fields. At electric field of $0\ \text{V}$, output light intensities are equal from the waveguide 1 and 2. At $-1\ \text{V}$ or $1\ \text{V}$, the cross talk become as large as 30dB for both TE and TM polarizations.

The number of $V_s L_a$ is another important parameter indicating the electric operation power of MMI waveguide switch, where V_s is the switching voltage and L is the active length. Y.Enami had reported that the switching voltage of EO polymer MZI switch to be $V_s L_a=2.9\ \text{Vcm}$ [8]. In our study, the $V_s L$ can reach to $0.5\ \text{V cm}$ due to the effective electrode area of $448\ \mu\text{m} \times 14\ \mu\text{m}$ in the MMI waveguide, where EO polymer had $r_{33}=100\ \text{pm/V}$.

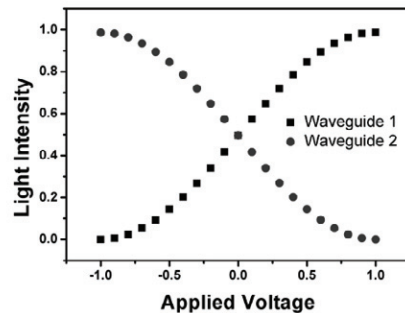


Figure 5. Output intensity as a function of applied voltage.

4. Conclusion

We have designed a new kind EO polymer optical switch based on MMI structure. The MMI structure was designed with tapered access waveguides to obtain high cross talk of the optical switching. The BPM simulation showed that the cross talk reached to 30dB for both TE and TM polarizations. The figure-of-merit was estimated to be $0.5\ \text{Vcm}$.

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